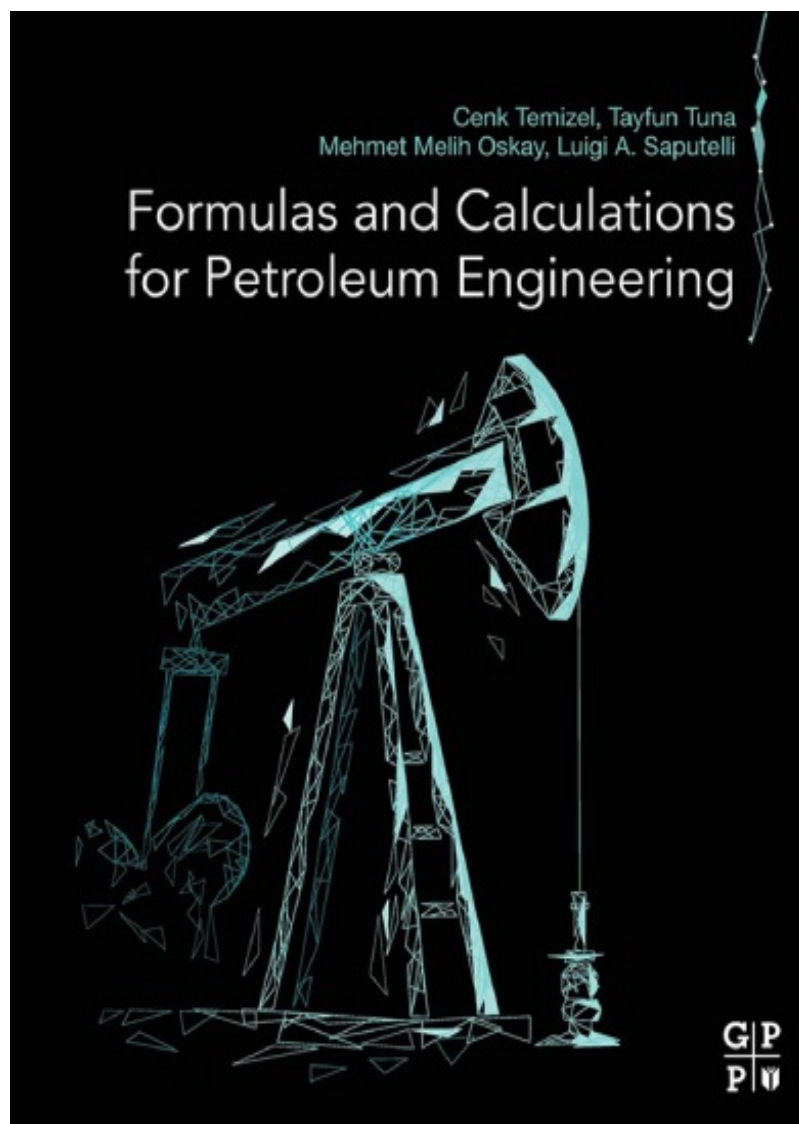


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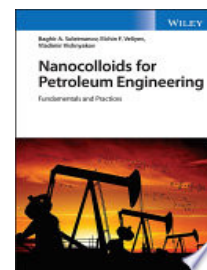


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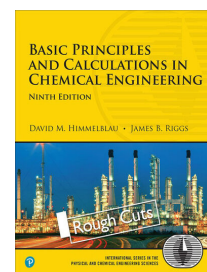
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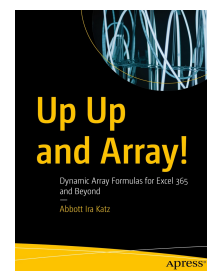
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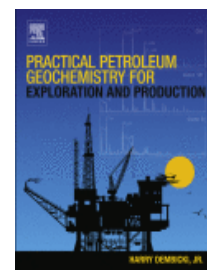
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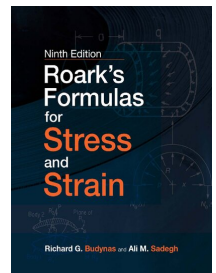
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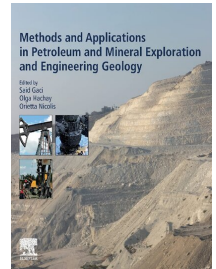
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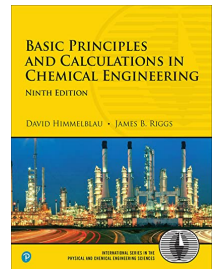
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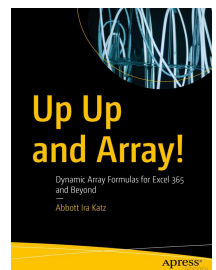
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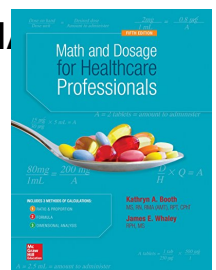
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Formulas and Calculations for Petroleum Engineering



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Foreword

Formulas and Calculations for Petroleum Engineering unlocks the capability for any petroleum engineering individual, experienced or not, to solve problems and locate quick answers, eliminating nonproductive time spent searching for that right calculation. Enhanced with lab data experiments, practice examples, and a complimentary online software toolbox, the book presents the most convenient and practical reference for all oil and gas phases of a given project. Covering the full spectrum, this reference gives single-point reference to all critical modules, including drilling, production, reservoir engineering, well testing, well logging, enhanced oil recovery, well completion, fracturing, fluid flow, and even petroleum economics.

ptlbx.com provides access to calculations of these formulas.

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Authors

This book is dedicated to my wife, my love, Saule who has supported me unconditionally in my endeavors and has been an inspiration for me in life with her love, care, and understanding and to my daughter Ada Ayca who has brought joy and happiness to our life and to my parents Yuksel and Rasim Temizel and my brother Efe for their continuous support and love.
Cenk Temizel

I am indebted to my wife Suhendan and to my daughter Ceyda for their unflagging support to finish this book.
Mehmet Melih Oskay

I dedicate this book to my parents Julia and Emilio, who are eternal symbols of unconditional love and true parenthood, from whom I learned what exemplary human values.
Luigi A. Saputelli

Reviewers

My effort that went into the completion of this book is dedicated to my wife Ezgi who assisted me with her love and patience, to Serkan who made me feel lucky to have an honest brother like him, and also to my beloved parents Fusun and Kaya Canbaz who gave their true love without any expectations and supported me with patience in any circumstances.
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I would like to express my deepest love and respect to especially my beloved parents and wife Elif who always has supported and inspired me to contribute to this book and my self-improvement in terms of both professional and personal ways during all my life.
Yildiray Palabiyik

Chapter 1

Reservoir engineering formulas and calculations

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1.1 API gravity

Input(s)

SG_o : Specific Gravity of Oil Phase (fraction)

Output(s)

API: API Gravity (dimensionless)

Formula(s)

$$API = \frac{141.5}{SG_o} - 131.5$$

Notes: $SG_o = \frac{\rho_{oil}}{\rho_{water}}$ at 60 F.

Reference: [Wikipedia.org](https://en.wikipedia.org/wiki/API_gravity).

1.2 Average permeability for linear flow—Layered beds

Input(s)

k_1 : Permeability for Layer 1 (mD)
 k_2 : Permeability for Layer 2 (mD)
 k_3 : Permeability for Layer 3 (mD)
 A_1 : Area of Layer 1 (ft²)
 A_2 : Area of Layer 2 (ft²)
 A_3 : Area of Layer 3 (ft²)

Output(s)

k_{avg} : Average Permeability in Linear Systems when there is no crossflow between layers (mD)

Formula(s)

$$k_{avg} = \frac{k_1 * A_1 + k_2 * A_2 + k_3 * A_3}{A_1 + A_2 + A_3}$$

Reference: Ahmed, T. (2006). *Reservoir Engineering Handbook*. Elsevier, Page: 238.

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1.3 Average permeability for linear flow—Series beds

Input(s)

- k_1 : Permeability for layer 1 (mD)
- k_2 : Permeability for layer 2 (mD)
- k_3 : Permeability for layer 3 (mD)
- L_1 : Length of layer 1 (ft)
- L_2 : Length of layer 2 (ft)
- L_3 : Length of layer 3 (ft)

Output(s)

- k_{avg} : Average Permeability in Linear Systems Series (mD)

Formula(s)

$$k_{avg} = \frac{L_1 + L_2 + L_3}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3}}$$

Reference: Ahmed, T. (2006). *Reservoir Engineering Handbook*. Elsevier, Page: 240.

1.4 Average permeability for parallel-layered systems

Input(s)

- k_1 : Permeability for Layer 1 (mD)
- k_2 : Permeability for Layer 2 (mD)
- k_3 : Permeability for Layer 3 (mD)
- h_1 : Height of Layer 1 (ft)
- h_2 : Height of Layer 2 (ft)
- h_3 : Height of Layer 3 (ft)

Output(s)

- k_{avg} : Average Permeability for Parallel-layered Systems (mD)

Formula(s)

$$k_{avg} = \frac{k_1 * h_1 + k_2 * h_2 + k_3 * h_3}{h_1 + h_2 + h_3}$$

Reference: Ahmed, T. (2006). *Reservoir Engineering Handbook*. Elsevier, Page: 237.

1.5 Average permeability in radial systems

Input(s)

- k_a : Permeability between r_w and r_a (mD)
- k_e : Permeability between r_e and r_a (mD)
- r_e : Drainage radius (ft)
- r_w : Well bore radius (ft)
- r_a : Radius lesser than r_e (ft)

Output(s)

k_{avg} : Average Permeability in Radial Systems Series (mD)

Formula(s)

$$k_{avg} = \frac{k_a * k_e * \ln\left(\frac{r_e}{r_w}\right)}{k_a * \ln\left(\frac{r_e}{r_a}\right) + k_e * \ln\left(\frac{r_a}{r_w}\right)}$$

Reference: *Applied Reservoir Engineering Vol. 1, Smith, Tracy & Farrar, Equation 7-7.*

1.6 Average temperature of a gas column**Input(s)**

T_t : Tubing Head Temperature (°R)

T_b : Wellbore Temperature (°R)

Output(s)

T : Arithmetic Average Temperature (°R)

Formula(s)

$$T = \frac{T_t + T_b}{2}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 199.*

1.7 Calculation of fractional flow curve**Input(s)**

μ_w : Water Viscosity (cP)

k_{rw} : Relative Permeability to Water (dimensionless)

k_{ro} : Relative Permeability to Oil (dimensionless)

μ_o : Oil Viscosity (cP)

Output(s)

f_w : Fraction of Total Flowing Stream Composed of Water (dimensionless)

Formula(s)

$$f_w = \frac{1}{1 + \frac{\mu_w * k_{ro}}{k_{rw} * \mu_o}}$$

Reference: *Craig Jr. F. F., 2004, the Reservoir Engineering Aspects of Waterflooding, Vol. 3. Richardson, Texas: Monograph Series, SPE, Page: 112.*

1.8 Capillary number

Input(s)

- μ_w : Viscosity of Displacing Fluid (cP)
 V : Characteristic Velocity (ft/D)
 σ_{ow} : Surface or Interfacial Tension of Oil and Water Phases (dyn/cm)

Output(s)

- N_c : Capillary Number (dimensionless)

Formula(s)

$$N_c = \frac{\mu_w * V}{\sigma_{ow}}$$

Reference: [Wikipedia.org](https://en.wikipedia.org/wiki/Capillary_number).

1.9 Capillary pressure

Input(s)

- σ : Fluid interfacial Tension (dyn/cm)
 θ : Angle of Wettability (degree)
 r : Radius of Capillary (cm)

Output(s)

- P_C : Capillary Pressure (dyn/cm)

Formula(s)

$$P_C = \frac{2 * \sigma * \cos(\theta)}{r}$$

Reference: [Wikipedia.org](https://en.wikipedia.org/wiki/Capillary_pressure).

1.10 Characteristic time for linear diffusion in reservoirs

Input(s)

- Φ : Porosity (fraction)
 β_f : Fluid Compressibility (1/psi)
 β_r : Rock Compressibility (1/psi)
 μ : Viscosity (cP)
 l : Characteristic Length Scale of Diffusion (ft)
 k : Permeability (mD)

Output(s)

- τ : Time (s)

Formula(s)

$$\tau = \frac{(\Phi * \beta_f + \beta_r) * \mu * I^2}{k}$$

Reference: *Zoback, M. D. Reservoir Geomechanics, Cambridge University Express, UK, Page: 41.*

1.11 Cole plot**Input(s)**

G: GIP (MSCF)
 E_g : Gas Expansion Term (bbl/MSCF)
 W_e : Water influx (bbl)

Output(s)

F: Underground Water Withdrawal (bbl)

Formula(s)

$$F = G * E_g + W_e$$

Reference: *Ahmed, T., McKinney, P. D. Advanced Reservoir Engineering, Gulf Publishing House, Burlington, MA, 2015.*

1.12 Communication between compartments in tight gas reservoirs**Input(s)**

G: Gas in Place (MSCF)
 E_g : Gas Expansion Term (bbl/MSCF)
 W_e : Cumulative Water Influx (bbl)

Output(s)

F: Underground Fluid Withdrawal (bbl)

Formula(s)

$$F = G * E_g + W_e$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 209.*

1.13 Communication factor in a compartment in tight gas reservoirs**Input(s)**

K: Permeability (mD)
A: Area (ft²)
T: Temperature (R)
L: Length of Compartment (ft)

Output(s)

C: Communication Factor (SCF/d/psi²/cP)

Formula(s)

$$C = \frac{0.111924 * k * A}{T * L}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 235.*

1.14 Compressibility drive in gas reservoirs

Input(s)

- G : Gas in place (MSCF)
- G_p : Gas Produced (MSCF)
- B_g : Gas Formation Volume Factor (MSCF/ft³)
- E_f : Gas Compressibility Drive (ft³/MSCF)

Output(s)

- CI: Compressibility Index (dimensionless)

Formula(s)

$$CI = \frac{G * E_f}{B_g * G_p}$$

Reference: *Ahmed, T. & McKinney, P.D. Advanced Reservoir Engineering, Gulf Publishing House, Burlington, MA, 2015.*

1.15 Correction factor—Hammerlindl

Input(s)

- G : Gas in Place (MSCF)
- G_p : Gas Produced (MSCF)
- B_g : Gas Formation Volume Factor (bbl/MSCF)
- $E_{f, w}$: Rock and Water Expansion Term (bbl/MSCF)

Output(s)

- CDI: Compressibility Drive Index (dimensionless)

Formula(s)

$$CDI = \frac{G * E_{f, w}}{G_p * B_g}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 211.*

1.16 Critical rate for horizontal Wells in edge-water drive reservoirs

Input(s)

- e_1 : Constant for C1 Equals +0.023 or – 0.023 (dimensionless)
- e_2 : Constant for C2 equals +0.0013 or – 0.0013 (dimensionless)
- e_3 : Constant for C3 equals +0.022 or – 0.022 (dimensionless)
- e_4 : Constant for C4 equals +0.0013 or – 0.0013 (dimensionless)
- $\Delta\rho$: Density Difference between water and oil or, oil and gas (gm/cc)

- h: Pay Zone Thickness (ft)
 L: Length of Well (ft)
 x_e : Distance between Horizontal Well and Constant Pressure Boundary (ft)
 μ_o : Oil Viscosity (cP)
 k_h : Vertical Permeability (mD)
 k_v : Horizontal Permeability (mD)

Output(s)

- c_1 : Dimensionless Constant for calculation (dimensionless)
 c_2 : Dimensionless Constant for calculation (dimensionless)
 c_3 : Dimensionless Constant for calculation (dimensionless)
 c_4 : Dimensionless Constant for calculation (dimensionless)
 q_c : Dimensionless Critical Rate per Unit length (STB/day/ft)
 q_o : Critical Rate (STB/day)
 z_c : Critical Height Representing the Difference between the Apex of the Gas/Water Crest from the Well Elevation (ft)

Formula(s)

$$c_1 = 1.4426 + e1$$

$$c_2 = -0.9439 + e2$$

$$c_3 = 0.4812 + e3$$

$$c_4 = -0.9534 + e4$$

$$q_c = c_1 * \left(\frac{x_e}{h * \left(\frac{k_h}{k_v} \right)^{0.5}} \right)^{c_2}$$

$$q_o = (4.888 * 10^{-4}) * \Delta \rho * h * (k_h * k_v)^{0.5} * L * \frac{q_c}{\mu_o}$$

$$z_c = c_3 * h * \left(\frac{x_e}{h * \left(\frac{k_h}{k_v} \right)^{0.5}} \right)^{c_4}$$

Reference: Joshi, S.D. 1991, *Horizontal Well Technology*. Tulsa, Oklahoma: PennWell Publishing Company. Chapter: 7, Page: 309, 310.

1.17 Crossflow index**Input(s)**

- N_{pcf} : Oil Recovery from Layered System with Crossflow (STB)
 N_{pncf} : Oil Recovery from Stratified System with No Crossflow (STB)
 N_{pu} : Oil Recovery from Uniform System with Average Permeability (STB)

Output(s)

- CI: Crossflow Index (dimensionless)

Formula(s)

$$CI = \frac{N_{pcf} - N_{pncf}}{N_{pu} - N_{pncf}}$$

Reference: Willhite, G.P. 1986. *Waterflooding*, Vol. 3. Richardson, Texas: Textbook Series, SPE, Chapter: 2, Page: 166.

1.18 Cumulative effective compressibility—Fetkovich

Input(s)

- S_{wi} : Initial Water Saturation (fraction)
- \bar{c}_w : Cumulative Total Water Compressibility (1/psi)
- M : Dimensionless Volume Ratio (dimensionless)
- \bar{c}_f : Total PV (Formation) Compressibility (psi⁻¹)

Output(s)

- \bar{c}_e : Effective Compressibility (1/psi)

Formula(s)

$$\bar{c}_e = \frac{S_{wi} * \bar{c}_w + M * (\bar{c}_f + \bar{c}_w) + \bar{c}_f}{1 - S_{wi}}$$

Reference: Ahmed, T., McKinney, P.D. 2005. *Advanced Reservoir Engineering*, Gulf Publishing of Elsevier, Chapter: 3, Page: 215,216.

1.19 Cumulative gas production—Tarnier's method

Input(s)

- N : Initial Oil-in Place (STB)
- R_s : Gas Solubility (SCF/STB)
- R_{si} : Initial Gas Solubility (SCF/STB)
- B_o : Oil Formation Volume Factor at the Assumed Reservoir Pressure (bbl/STB)
- B_{oi} : Oil Formation Volume Factor at Initial Reservoir Pressure (bbl/STB)
- B_g : Gas Formation Volume Factor at the Assumed Reservoir Pressure (bbl/SCF)
- N_p : Cumulative Oil Production (STB)

Output(s)

- G_p : Cumulative Gas Production (SCF)

Formula(s)

$$G_p = N * \left[(R_{si} - R_s) - \left(\frac{B_{oi} - B_o}{B_g} \right) \right] - N_p * \left[\frac{B_o}{B_g} - R_s \right]$$

Reference: Ahmed, T., McKinney, P.D. 2005. *Advanced Reservoir Engineering*, Gulf Publishing of Elsevier, Chapter: 5, Page: 340.

1.20 Cumulative oil production—Undersaturated oil reservoirs

Input(s)

- N : Initial Oil-in Place (STB)
 c_e : Effective Compressibility (1/psi)
 B_o : Oil Formation Volume Factor at the Assumed Reservoir Pressure (bbl/STB)
 B_{oi} : Oil Formation Volume Factor at Initial Reservoir Pressure (bbl/STB)
 ΔP : Pressure Differential (psi)

Output(s)

- N_p : Cumulative Oil Production (STB)

Formula(s)

$$N_p = N * c_e * \left(\frac{B_o}{B_{oi}} \right) * \Delta P$$

Reference: Ahmed, T., McKinney, P.D. 2005. *Advanced Reservoir Engineering*, Gulf Publishing of Elsevier, Chapter: 5, Page: 333.

1.21 Deliverability equation for shallow gas reservoirs

Input(s)

- k : Permeability (mD)
 h : Thickness (ft)
 T : Temperature (°R)
 μ : Viscosity (cP)
 z : Compressibility Factor (dimensionless)
 r_e : Radius of Drainage Area (ft)
 r_w : Wellbore Radius (ft)

Output(s)

- C : Performance Coefficient (dimensionless)

Formula(s)

$$C = \frac{k * h}{1422 * T * \mu_g * Z * \left(\ln \left(\frac{r_e}{r_w} \right) - 0.5 \right)}$$

Reference: Ahmed, T., McKinney, P.D. 2005. *Advanced Reservoir Engineering*, Gulf Publishing of Elsevier, Chapter: 3, Page: 287.

1.22 Dimensionless pressure—Kamal and Brigham

Input(s)

- Q : Flow Rate (STB/day)
 \bar{k} : Average Permeability (mD)
 h : Thickness (ft)

B: Formation Volume Factor (bbl/STB)
 μ : Viscosity (cP)
 ΔP : Pressure Difference (psi)

Output(s)

ΔP_d : Dimensionless Pressure (dimensionless)

Formula(s)

$$\Delta P_d = \frac{\bar{k} * h * \Delta P}{141.2 * Q * \mu * B}$$

Reference: Ahmed, T., McKinney, P.D. 2005. *Advanced Reservoir Engineering*, Gulf Publishing of Elsevier, Chapter: 1, Page: 125.

1.23 Dimensionless radius of radial flow—Constant-rate production

Input(s)

r: Effective Radius/Reservoir Radius (ft)
 r_w : Wellbore Radius (ft)

Output(s)

r_d : Dimensionless Radius (dimensionless)

Formula(s)

$$r_d = \frac{r}{r_w}$$

Reference: Lee, J., Rollins, J. B., & Spivey, J. P. (2003). *Pressure Transient Testing (Vol. 9)*. Richardson, Texas: Society of Petroleum Engineers, Page: 8.

1.24 Dimensionless time—Myhill and Stegemeier's method

Input(s)

M_s : Volumetric Heat Capacity of Steam (btu/ft³ K)
 M_R : Volumetric Heat Capacity of the Reservoir (btu/ft³ K)
 α_s : Overburden Heat Transfer Coefficient (ft²/d)
 h_i : Thickness of Column (ft)
t: Time (day)

Output(s)

t_D : Dimensionless Time (dimensionless)

Formula(s)

$$t_D = 4 * \left(\frac{M_s}{M_R} \right)^2 * \left(\frac{\alpha_s}{h_i^2} \right) * t$$

Reference: Prats, M. 1986. *Thermal Recovery*. Society of Petroleum Engineers, New York, Chapter: 5, Page: 44.

1.25 Dimensionless time for interference testing in homogeneous reservoirs—Earlougher

Input(s)

- k: Permeability (mD)
- ϕ : Porosity (fraction)
- t: Time (h)
- k: Overall Production (mD)
- μ : Viscosity (cP)
- c_t : Total Compressibility (1/psi)
- r_w : Wellbore Radius (ft)

Output(s)

- t_D : Dimensionless Time (dimensionless)

Formula(s)

$$t_D = \frac{0.0002637 * k * t}{\phi * c_t * \mu * (r_w^2)}$$

Reference: Ahmed, T., McKinney, P.D. 2005. *Advanced Reservoir Engineering*, Gulf Publishing of Elsevier, Chapter: 1, Page: 117.

1.26 Dimensionless vertical well critical rate correlations—Hoyland, Papatzacos, and Skjaeveland

Input(s)

- h: Oil Column Thickness (ft)
- k_h : Effective Oil Permeability (mD)
- ρ_w : Water Density (g/cc)
- μ_o : Oil Viscosity (cP)
- ρ_o : Oil Density (g/cc)
- B_o : Oil Formation Volume Factor (RB/STB)
- q_o : Critical Oil Rate (STB/day)

Output(s)

- Q_{oD} : Dimensionless Critical Rate (dimensionless)

Formula(s)

$$Q_{oD} = 651.4 * \mu_o * B_o * \frac{q_o}{h^2 * (\rho_w - \rho_o) * k_h}$$

Reference: *Reservoir Engineering Handbook, Fourth Edition*, Ahmed, Page: 607.

1.27 Dimensionless wellbore storage coefficient of radial flow—Constant-rate production

Input(s)

- h: Reservoir Thickness (ft)
- C: Wellbore Storage Coefficient (STB/psi)

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